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Original article

Dissipative energy loss within the left ventricle detected by vector flow mapping in children: Normal values and effects of age and heart rate

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ABSTRACT

Background: Vector flow mapping (VFM) is a novel echocardiographic technology which enables visualization of the intraventricular flow velocity vector. Dissipative energy loss (EL) derived from the velocity vector field of intraventricular blood flow is considered to reflect the efficiency of blood flow, and could be an indicator of left ventricular function. We aimed to determine the reference values of the EL derived from VFM within the left ventricle.

Methods: VFM analysis was performed using echocardiography in 64 healthy children. The velocity vector fields of the intra-left ventricular blood flow were obtained from the apical 5-chamber view, and the EL values during systole and diastole were calculated. The measurements were averaged over three cardiac cycles, and indexed to body surface area (BSA).

Results: The mean subject age was 6.8 ± 4.3 years. The mean EL was 4.10 ± 2.35 mW/m/m^2 BSA during systole and 16.24 ± 11.63 mW/m/m^2 BSA during diastole. On multivariate analysis, age and heart rate (HR) were independent predictors of systolic EL, whereas age, HR, and E wave peak velocity were independent predictors of diastolic EL. The regression equations used to predict the BSA-indexed systolic and diastolic EL were as follows: $\log_{10}$ (systolic EL) = −0.0332 − 0.00213 × age (months) + 0.00789 × HR (beats/min) (adjusted R^2, 0.833; $p < 0.0001$); and $\log_{10}$ (diastolic EL) = 0.277 − 0.00346 × age (months) + 0.00570 × HR HR (beats/min) + 0.00564 × E wave peak velocity (cm/s) (adjusted R^2, 0.867; $p < 0.0001$).

Conclusions: The systolic and diastolic EL were positively correlated with HR and negatively correlated with age. Moreover, the diastolic EL was positively correlated with the E wave peak velocity. The present study provides reference values for the systolic and diastolic EL that can be used in future studies examining patients with heart disease.

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Introduction

The intraventricular blood flow pattern changes according to an alteration in left ventricular (LV) function. The abnormal LV intracavitary flow acceleration due to cavity squeezing, which is observed in patients after valve replacement for aortic stenosis, is known to be associated with low output syndrome and high hospital mortality [1,2]. Studies using Doppler echocardiography [3] and magnetic resonance velocity mapping [4] showed an increased deceleration of early diastolic transmitral filling flow toward the apex in the presence of LV diastolic dysfunction. Thus, changes in the LV intracavitary flow pattern may have clinical relevance. However, the diagnostic utility of intraventricular blood flow analysis remains undetermined due to a lack of standardized methods for evaluating the intraventricular blood flow pattern.

Vector flow mapping (VFM) is a novel echocardiographic technology, which enables visualization of the intraventricular flow velocity vector using color Doppler and speckle tracking data [5,6]. The dissipative energy loss (EL)—derived from the intraventricular flow velocity vector field—is a flow dynamic parameter that reflects spatial dispersion of intraventricular

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blood flow [5]. A quantitative assessment of the LV intracavitary blood flow in terms of EL could provide insight into LV function. This study aimed to establish a reference value for EL within the left ventricle in healthy children.

Methods

Subjects

We retrospectively searched our echocardiography database for children aged 1–15 years who underwent echocardiographic screening for a heart murmur or chest pain. The medical records of the subjects were reviewed, and clinical data including sex, age, body weight, height, and echocardiographic measurements were collected. The subjects were included in the study if they had a structurally normal heart, sinus rhythm, LV fraction shortening (LVFS) >0.25, and body weight and height between the 3rd and 97th percentiles [7].

The institutional Ethics Committee approved our retrospective study, and waived the requirement for written informed consent.

Echocardiographic examination

The echocardiographic examinations were performed with a ProSound alpha-7 ultrasonography (Hitachi-Aloka Medical Co. Ltd., Tokyo, Japan) equipped with a 5-MHz transducer according to the standard method recommended by the American Society of Echocardiography [8]. If required, the infants and young children were sedated with triclofos sodium before the examination. Digitized two-dimensional color Doppler cineloop images obtained from the apical 5-chamber view with simultaneous electrocardiographic recording were stored in an image server, which was available for off-line VFM analysis. The Nyquist limit for two-dimensional color Doppler imaging was set high enough to mitigate the aliasing phenomenon. The collected echocardiographic measurements included LVFS, peak blood flow velocities at the mitral valve during early filling (E wave) and in late diastole (A wave), E/A ratio, peak myocardial velocities at the septal mitral annulus in early (e') and late diastole (a'), and E/e' ratio.

Vector flow mapping analysis

Two-dimensional color Doppler cineloop images obtained from the apical 5-chamber view were analyzed with the commercially available VFM analysis software (Hitach-Aloka Medical) to obtain the velocity vector fields of LV intracavitary blood flow. One cardiac cycle was selected for the analysis by determining two consecutive QRS complexes as the beginning and ending points. The heart rate (HR) was calculated based on the RR interval of the cardiac cycle. The ventricular cavity-endocardial border was manually traced on the beginning frame, and two-dimensional speckle tracking was applied to determine the cardiac wall motion. If the aliasing phenomenon was observed in color Doppler data, the aliased area was manually corrected. The software computed the velocity vector fields of the LV intracavitary blood flow based on a system developed by Itatani et al. [5]. In brief, a two-dimensional continuity equation was applied to the color Doppler data using speckle tracking as the boundary conditions, and the velocity component perpendicular to the echo beam line was obtained.

EL calculation

From the velocity vector fields of the interventricular blood flow, EL was calculated for each frame of the cineloop image. The EL is defined as follows, where μ indicates blood viscosity, which was set as 0.004 Pa s [5]:

$$\mathrm{EL} = \mu \sum_{i,j} \int \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)^2 dx\,dy$$

A frame at which the mitral valve began to open was determined as the beginning of diastole. The systolic and diastolic EL within the left ventricle were calculated as the arithmetic means of the EL during systole and diastole. The measurements were averaged over three cardiac cycles, and indexed to body surface area (BSA).

The fluid energy of blood flow consists of potential energy (generated mainly by the static pressure in a circulatory system) and kinetic energy (generated by the dynamic pressure). Potential energy and kinetic energy can convert with each other. Turbulent flow results in irreversible loss of the total fluid energy [9]. The EL we calculated in this study was the amount of fluid energy that was lost and dissipated as heat in the left ventricle.

Ideally, the EL should be assessed as a ratio to the total fluid energy. However, total fluid energy of blood flow cannot be measured unless we know the temporal and spatial distribution of both pressure and flow velocity in the left ventricle. In this study, the EL values were indexed to BSA so that the absolute value of EL can be compared among the pediatric population with widely varied body size. Potential and kinetic energies increase proportionately with a mass of the blood within the left ventricle. As a result a subject with a larger body size would have a greater total fluid energy, and hence a greater EL.

The EL is a flow dynamic parameter that reflects spatial dispersion of the intraventricular blood flow; a greater EL is observed with more precipitous changes in blood flow velocity and direction. Moreover, the EL represents the rate at which energy is expended; hence, it is measured in watts (W). Since the VFM analysis is based on two-dimensional flow assumption, the EL derived from the VFM analysis is expressed as W/m.

Fig. 1 illustrates a transition of the EL throughout one cardiac cycle in a 9-year-old boy. At the bottom of the figure, the velocity vector fields of LV intracavitary blood flow obtained by VFM analysis are superimposed.

Statistical analysis

The results are expressed as mean ± SD. For the statistical analysis, the EL values were logarithmically transformed. The correlations between the EL and age, HR, and echocardiographic measurements were evaluated by Pearson's correlation coefficient. To determine the independent variables that correlate with the EL, a stepwise multivariate linear regression analysis was performed using the following variables: age, HR, LVFS, and E wave peak velocity. Moreover, we investigated whether there was an interaction between the independent variables by adding bilinear terms to the regression analysis. Based on the multivariate linear regression analysis, the regression equations for the systolic and diastolic EL were obtained. A p-value of <0.05 was considered statistically significant. All statistical analyses were performed using R version 2.13.0.

Reproducibility

To assess intra-observer variability, the VFM analysis and EL calculation were repeated in 10 randomly selected cineloop images. The repeated analysis was performed >1 week after the initial analysis. Furthermore, the VFM analysis of the cineloop images was performed by a second pediatric cardiologist, and the inter-observer variability was evaluated. The intra-observer and inter-observer variability were evaluated as the mean percentage error, which was an absolute difference divided by the mean of the

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